Pacific Science (2000), vol. 54, no. 4: 423–442

Stratigraphy and Whole-Rock Amino Acid Geochronology of Key Holocene and Last Interglacial Carbonate Deposits in the Hawaiian Islands[1]

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ABSTRACT: We evaluated the utility of whole-rock amino acid racemization as a method for the stratigraphic correlation and dating of carbonate sediments in the Hawaiian Islands. D-alloisoleucine/L-isoleucine (A/I) ratios were determined for carbonate sand and sandstone samples from 25 localities in the archipelago. The superposition of A/I ratios within stratigraphic sections and the regional concordance of ratios within geological formations support the integrity of the method. To correlate the A/I ratios with an absolute chronology, comparisons were made with previously published uranium series dates on corals and with ^{14}C dates on carbonate sand and organic material, including several new dates reported herein. The A/I mean from four marine isotope stage (MIS) 5e U-series calibration sites was 0.505 ± 0.027 ($n = 11$), and 12 "test sites" of previously uncertain or speculative geochronological age yielded an A/I mean of 0.445 ± 0.058 ($n = 17$). Similarly, extensive Holocene dunes on Moloka'i and Kaua'i were correlated by a mean A/I ratio of 0.266 ± 0.022 ($n = 8$) and equated with a ^{14}C bulk sediment mean age of 8600 yr B.P. Our results indicate that the eolian dunes currently exposed in various localities in the Islands originated primarily during two major periods of dune formation, the last interglacial (MIS 5e) and the early Holocene (MIS 1). MIS 5e and MIS 1 A/I ratios from the Hawaiian Islands show close agreement with previous whole-rock studies in Bermuda and the Bahamas. We discuss these results in terms of their relevance to models of lithospheric flexure and to imposing constraints on the time frame for the extinction of fossil birds.

GEOCHRONOLOGY AND SEA-LEVEL history have been particularly important in the scientific history of the Hawaiian Islands. Thermal ionization mass spectrometric (TIMS) and alpha U-series dates augmented by ^{14}C dates from the Holocene (marine isotope stage 1 [MIS 1]) provide a temporal framework for important events in geology and paleobiology during the late Quaternary. More than 70 U-series dates have been obtained from last interglacial (MIS 5e, ca. 125 ka [thousand years] old) deposits from O'ahu (Ku et al. 1974, Easton and Ku 1981, Muhs and Szabo 1994, Szabo et al. 1994). ^{14}C dates from terrestrial sites on O'ahu, Moloka'i, Hawai'i, Maui, and Kaua'i (Olson and James 1982*a,b*, James et al. 1987, Paxinos 1998; this study, Table 1) have placed constraints on the recent extinctions of dozens of species of fossil birds.

Nonetheless, the age of many important sites remains uncertain. U-series dating is most effective on coral samples, ideally those collected in growth position and composed of pure aragonite. However, like other relatively stable carbonate-producing areas (Bermuda and the Bahamas), the majority of deposits in the Hawaiian Islands are not corals or coral reefs, but carbonate grainstone deposited in

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TABLE 1

^{14}C DATES FROM FOSSIL SITES IN O'AHU, MOLOKA'I, AND KAUA'I

ISLAND (REF NO.)	LOCALITY (AAR SAMPLE NO.)	FOSSIL SITE	SAMPLE NO.	SAMPLE MATERIAL	YR B.P. $\pm 1\sigma$	= A/I RATIO (TABLE 2)
O'ahu (2)	'Ōhikilolo (OOH1e)		Beta-130725	Organic clay beneath +2 m beachrock	4,990 ± 60	>0.215[a]
Kaua'i (2)	Makawehi dunes (KMW1c)	K2	Beta-122589	Calcareous sand	8,900 ± 70	0.245
Kaua'i (1)	Makawehi dunes	K2	SI-3792	Land snail shells	6,740 ± 80	
Kaua'i (1)	Makawehi dunes	K2	SI-3793	Land crab claws	5,145 ± 60	
Kaua'i (1)	Makawehi dunes	K2	AA-2976 (AMS)	Bone, *Branta sandvicensis*	4,690 ± 100	
Moloka'i (2)	'Īlio Point (MIP6x)		Beta-122591	Calcareous sand	12,740 ± 90	0.277
Moloka'i (2)	'Īlio Point (MIP4x)		Beta-122590	Calcareous sand	12,710 ± 90	0.308
Moloka'i (1)	'Īlio Point	Site 20	SI-3791B	Large land snail shells	5,510 ± 65	
Moloka'i (1)	'Īlio Point	Site 20	SI-3791A	Small land snail shells	5,245 ± 65	
Moloka'i (4)	Kaunakakai West		Beta-60345	Calcareous sand	4,750 ± 70	0.270
			Beta-71518	Calcareous sand	5,730 ± 80	
Moloka'i (2)	Mo'omomi (MMM4x)		Beta-122592	Calcareous sand	8,360 ± 60	0.246
Moloka'i (1, 3)	Mo'omomi	Site 1	HIG-35	Land snail shells	25,150 ± 1000	

Note: Uncalibrated ^{14}C ages are younger than their calendar ages. Because of the marine reservoir effect, bulk calcareous sediment ages are several hundred years younger than the quoted age. References: (1) Olson and James (1982*a,b*); (2) new ^{14}C ages from this study; (3) Stearns (1973); (4) Fletcher et al. (1999).

[a] A/I ratio from beachrock truncating dated organic clay.

subtidal, beach, or eolian environments. The need to date numerous sites lacking in age control, as well as the availability of several previously well-dated sites, provides incentive for the application of new dating techniques such as whole-rock aminostratigraphy (Hearty et al. 1992, Hearty 1998).

The Hawaiian Islands (Figure 1) are a succession of hot-spot volcanoes that, after formation, were conveyed WNW with the migration of the Pacific plate (Jackson et al. 1980). Those islands located farther west of the hot spot are progressively older; for example, the ages of formation of Moloka'i, O'ahu, and Kaua'i are about 1.6, 3.0, and 5.0 my (million years ago), respectively (Clague and Dalrymple 1989). A "rejuvenation" phase of volcanic activity occurred on these islands well into the middle and late Pleistocene. As they aged, the volcanoes accumulated greater volumes of limestone deposits (Darwin 1839) that were emplaced on shorelines, mainly during high stands of sea level (Bretz 1960).

According to the lithospheric model of Grigg and Jones (1997) (Figure 2), the islands of Lana'i, Moloka'i, and O'ahu should experience net uplift, whereas Hawai'i and Maui, lying within the subsidence moat, and Kaua'i, lying beyond the forebulge ridge, should experience net subsidence during the late Quaternary. This and other lithospheric models (Watts and ten Brink 1989) can be tested, provided sufficient age and sea level information is available.

Anthropogenic perturbations of Hawaiian ecosystems caused massive extinctions of birds and other elements of the biota in the approximately 1500 yr since the arrival of the first humans in the archipelago (Athens

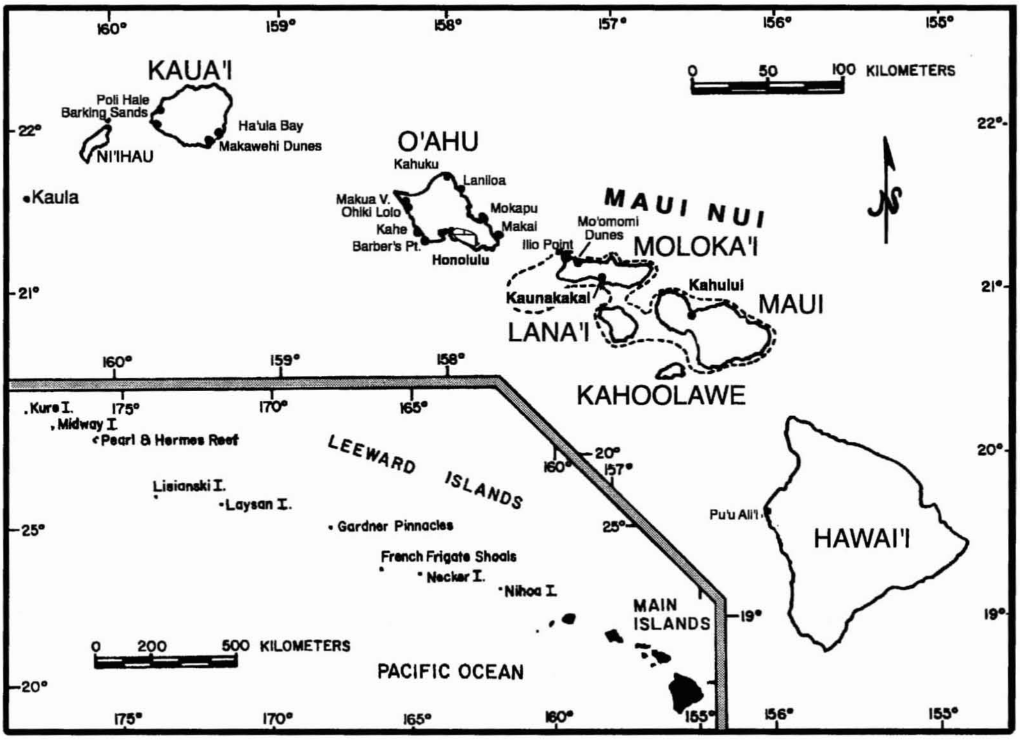

FIGURE 1. Location map of study sites in the Hawaiian islands (modified from Olson and James [1982*a*]).

1997). The extent of avian extinctions has been revealed in Pleistocene and mainly late Holocene fossil deposits on six of the main Hawaiian islands. Carbonate dunes record an important chapter in the unfolding story of prehistoric human-induced extinctions, particularly of birds, in the Hawaiian Archipelago (Olson and James 1982*a,b*, 1991, James and Olson 1991). As yet, the only fossil bird remains collected on the island of Moloka'i are from dune deposits in the vicinity of Mo'omomi Beach and 'Īlio Point. Until recently (Burney et al. 2000), the only fossil record of birds from the island of Kaua'i was likewise obtained entirely from dune deposits at Makawehi on the southeastern coast. Knowledge of the geology and age of these deposits is important for establishing the chronology and probable causes of extinction, as well as interpreting the past environmental conditions under which now-extinct species flourished. We use the whole-rock amino acid racemization (AAR) geochronology results to constrain the ages of terrestrial fossil deposits in Hawaiian dunes.

AAR ANALYTICAL PROCEDURES

Whole-rock aminostratigraphy has been used to unravel Quaternary stratigraphic questions in Bermuda (Hearty et al. 1992) and the Bahamas (Hearty 1998, Hearty and Kaufman 2000) and has been effective for the estimation and correlation of ages of deposits on diverse islands. For example, in the Bahamas over 100 whole-rock D-alloisoleucine/L-isoleucine (A/I) ratios from stratigraphically defined last interglacial MIS 5e oolite yielded a consistent and unambiguous correlation across 700 km of the Bahamas Archipelago (Figure 3). The individual and collective last interglacial A/I means from 13 major island groups do not overlap with

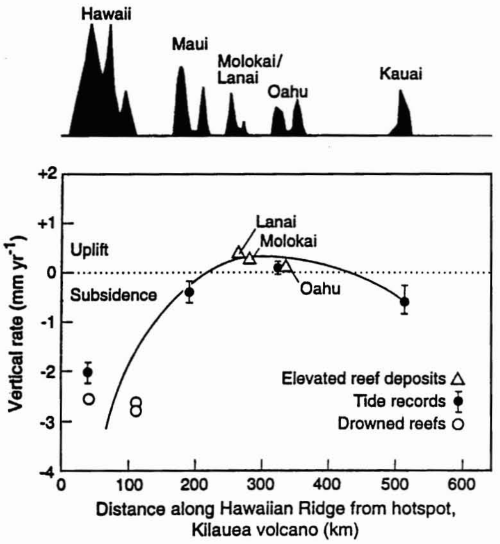

FIGURE 2. Lithospheric flexure model of Grigg and Jones (1997) showing subsidence of Hawai'i and Maui within the moat of the Big Island; uplift of Lāna'i, Moloka'i, and O'ahu in the forebulge region; and subsidence of Kaua'i beyond the forebulge area. In general terms, our findings support this model.

either younger or older modal classes of A/I ratios or "aminozones" (see Hearty et al. 1986).

The underlying theory and various applications of the AAR method are summarized in Rutter and Blackwell (1995). The AAR method is based on the racemization of amino acids preserved in biominerals (Hare and Mitterer 1967). Through time, L-amino acids racemize (or, more specifically in the case of the amino acid isoleucine, epimerize) to their D-isomer form. The ratio of A/I amino acids measures the extent of epimerization. In the epimerization reaction of isoleucine, the A/I ratio is initially zero (0.011 with laboratory preparation) in truly modern organisms and increases to an equilibrium A/I ratio of about 1.3 with time after death of an organism. Because the whole-rock method analyzes aggregates of comminuted skeletal and precipitated carbonate grains that form offshore over time, entirely "modern" material, even on active beaches, is not expected. Thus, each whole-rock sample will have some "inherited" age. The implicit assumption is that the inherited age is similar for all samples of the same age. As seen in the results, the local and regional consistency of A/I ratios from equal-age units supports the validity of this assumption *in most cases.*

Like many chemical reactions, the rate of racemization/epimerization depends on the ambient temperature of the reaction medium. Thus, sites at lower latitudes and warmer temperatures are expected to yield incrementally higher ratios. Single A/I ratios without stratigraphic context are obviously unacceptable indicators of age or correlation. However, within a local or regional setting where several separate sites are determined to be stratigraphic equivalents by field geology, single ratios from each of several outcrops that yield similar A/I ratios are considered to be an effective demonstration of the method.

The Hawaiian Islands surveyed in this study (Hawai'i, Maui, O'ahu, Moloka'i, and Kaua'i) lie in the Tropics between 20.5° and 22° N. Relative to the Hawaiian Islands, most of the Bahamas are situated at higher, cooler latitudes (28° to 23° N), but also extend southward to similar latitudes (Inagua, at 21° N). Bermuda lies well north of the Tropics and near the limit of reef growth at 32.3° N. Historical temperature records from the Hawaiian Islands generally yield higher (25°C) mean annual temperatures (MATs) than Bermuda (20°C) or the Bahamas (22–24°C), and notable intraisland MAT differences are evident in Hawai'i. Because of the inferred difference in temperature histories between these distant localities, we cannot correlate A/I ratios directly. Instead, the kinetics of racemization predict that deposits from Hawai'i should have higher ratios than deposits of similar age in the Bahamas, which have higher ratios than those in Bermuda (Hearty et al. 1992, Hearty 1998).

Sample Preparation and Analysis

The whole-rock sample preparation procedure follows that of Hearty et al. (1992) and Hearty (1998). However, in contrast to previous study sites in Bermuda and the Bahamas, some samples from the Hawaiian

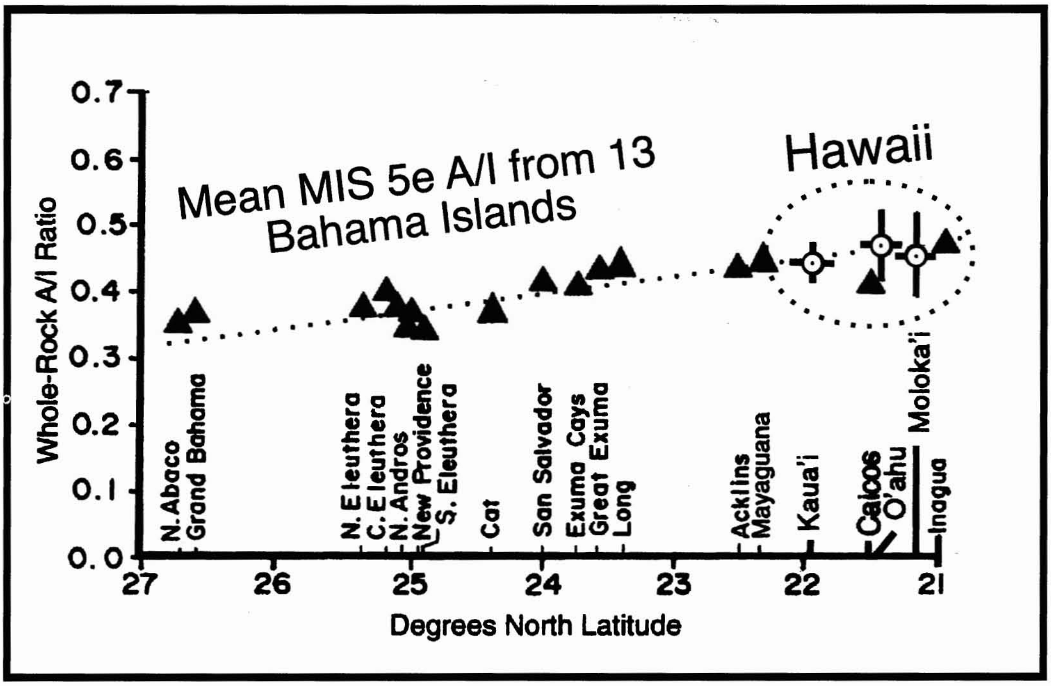

FIGURE 3. Graph of mean whole-rock A/I ratios from MIS 5e deposits in the Bahamas (triangles), with comparison of mean whole-rock ratios at similar latitudes from Kaua'i, O'ahu, and Moloka'i (solid dots with error bars).

Islands contain substantial percentages of volcanic grains, ranging from 1% to over 50%. High percentages of chemically active and insoluble volcanic fraction have the potential to inhibit optimum performance of high-pressure liquid chromatography (HPLC). In anticipation of this problem, samples from Mōkapu Point were analyzed both in their entirety and as pure carbonate samples sieved and picked or magnetically separated. Samples with high percentages of volcanic grains consistently yielded lower and less-predictable A/I ratios than those in which the volcanic grains were separated from the samples. Thus, only ratios from the carbonate fraction are reported here (Table 2).

Limestone samples were gently crushed and disaggregated with a mortar and pestle, and sieved to obtain the 250 to 850 μm textural fraction. Repeated gentle milling, microscopic examination, and sieving at the optimal size effectively separated grains from cements. Thus, the potential influence of younger amino acids contained in secondary cements is largely excluded.

Samples were analyzed at Northern Arizona University (NAU)'s Amino Acid Geochronology Laboratory according to the following procedure. For each sample, approximately 100 mg of sediment was first leached to remove 30% of sample weight with dilute hydrochloric acid. HCl leaching further reduced the possibility of contamination by removing any remaining cements and/or other organic residues on grain surfaces. Approximated 30-mg samples were dissolved in 6.25 μM norleucine (a nonprotein amino acid used as an internal standard) in 7M HCl to yield a 6M solution. Samples were flushed with N_2 to inhibit oxidation, sealed in sterile vials, hydrolyzed at 110°C for 22 hr, and then evaporated under N_2 in a heat block or under a vacuum. After rehydration, samples were injected onto an ion-exchange liquid chromatograph that employs postcolumn derivitization in

TABLE 2

WHOLE-ROCK A/I DATA FROM HOLOCENE AND PLEISTOCENE SITES IN THE HAWAIIAN ISLANDS (CALIBRATION OF A/I RATIOS IS PROVIDED BY ^{14}C AND U-SERIES AGES)

LOCALITY LABORATORY NO.	FIELD NO.	A/I RATIO ± 1σ (ANALYTICAL ERROR[a])	AGE (^{14}C, U-SERIES OR STRATIGRAPHIC)
Holocene MIS 1 A/Is			
Hawai'i			
Pu'u Ali'i Beach			
2835	HPA1z	0.105 ± 0.003	Modern beach
2833	HPA1y	0.126 ± 0.007	Recent dune
Maui			
Community college, Kahului			
2831	AMCC1c	0.372 ± 0.007[b]	Mid-1 eolianite
2836	AMNH1a	0.349 ± 0.012[b]	Mid-1 eolianite
O'ahu			
Makai Range Pier			
2501	OMI1z	0.103 ± 0.011	Modern beach
'Ōhikilolo			
2705	OOH2d	0.215 ± 0.001	+2 m beachrock, ≤4,990 yr BP
Moloka'i			
'Īlio Point			
2518	MIP5z	0.088 ± 0.001	Modern beach
2516	MIP2x	0.262 ± 0.001	Mid-1 dune
—	MIP4x	0.308 ± 0.000	12,710 ± 90 yr BP
2519	MIP6x	0.277 ± 0.001	12,740 ± 90 yr BP
—	Site 20		5,510 ± 65 yr BP (land snails)
—	Site 20		5,245 ± 65 yr BP (land snails)
Mo'omomi			
2988	MMM5z	0.126 ± 0.005	Modern beach sand
2515	MMM3x	0.274 ± 0.010	Mid-1 dune
2679A	MMM4x	0.235 ± 0.008	8,360 ± 60 yr BP
2679B	MMM4x	0.257 ± 0.010	8,360 ± 60 yr BP
Kaunakakai			
2987	MAI1x	0.270 ± 0.008	4,750 ± 70; 5,730 ± 80 yr BP[c]
Kaua'i			
Hidden Valley			
2523	KHV1x	0.080 ± 0.002	Submodern dune
Polihale Dunes (Barking Sands)			
2524	KPH1x	0.153 ± 0.000	Submodern dune
Makawehi (Site K2)			
2525A	KMW1c	0.245 ± 0.003	8,900 ± 70 yr BP[d]
—	Site K2		6,740 ± 80 yr BP (land snails)
—	Site K2		5,145 ± 60 yr BP (crab claws)
—	Site K2		4,690 ± 100 yr BP (*B. sandvicensis*)
Last interglacial MIS 5a A/Is			
Moloka'i			
Mo'omomi Dunes			
2520C/2843	MMM1c	0.329 ± 0.005	MIS 5a eolianite
2520D/2842	MMM1e	0.340 ± 0.008	MIS 5a eolianite
2989	MMM5c	0.342 ± 0.029	MIS 5a eolianite
2990	MMM2d	0.343 ± 0.013	MIS 5a eolianite
Last interglacial MIS 5e A/Is			
O'ahu (MIS 5e calibration sites are referenced)			
Mōkapu Point (Muhs and Szabo 1994, Szabo et al. 1994)			
2510D	OKP2b (2)	0.509 ± 0.028	120 ka; w/o volcanics
2510C	OKP2b (2)	0.523 ± 0.015	120 ka; w/o volcanics
2511C	OKP2a (1)	0.541 ± 0.013	130 ka; w/o volcanics
2511D	OKP2a (1)	0.532 ± 0.000	130 ka; w/o volcanics

TABLE 2 (continued)

LOCALITY LABORATORY NO.	FIELD NO.	A/I RATIO ± 1σ (ANALYTICAL ERROR[a])	AGE (^{14}C, U-SERIES OR STRATIGRAPHIC)
Barbers Point (Sherman et al. 1993)			
2509	OBA1c (2)	0.460 ± 0.041	117 ka mudstone
2508B	OBA1b (2)	0.493 ± 0.008	140–120? ka beachrock
2508C	OBA1b (2)	0.493 ± 0.018	140–120? ka beachrock
2508A	OBA1b (1)	0.479 ± 0.014	140 ka grainstone
Makai Range Pier (Szabo et al. 1994)			
2503	OMI1a	0.504 ± 0.021	134 ka
Kahe Point Beach Park (Szabo et al. 1994)			
2841	OHE2b	0.480 ± 0.023	MIS 5e reef
2994	OHE4c	0.627 ± 0.013[d]	(~120 ka) MIS 5e congl.
2840	OHE1c	0.608 ± 0.013[d]	(~120 ka) MIS 5e congl.
2993	OHE1c	0.543 ± 0.018[d]	(~120 ka) MIS 5e congl.
Kahuku Point (Ku et al. 1976, Szabo et al. 1994)			
2704A	OKK1c	0.397 ± 0.004	(<121 ka) MIS 5e or 5a dune?
2704B	OKK1e	0.397 ± 0.006	(<121 ka) MIS 5e or 5a dune?
Laniloa Peninsula			
2703A	OLA1c	0.379 ± 0.003	MIS 5e or 5a? eolianite
2502	OLA1a	0.640 ± 0.019	Mid-Pleistocene (MIS 7/9)
Mākua Valley			
2992	OMU1a	0.550 ± 0.008	MIS 5e shoreline at +9 m
Maui			
Kahului			
2832	AMCC1a	0.378 ± 0.017	MIS 5e eolianite
2837	AMZB1a	0.380 ± 0.021	MIS 5e eolianite
Moloka'i			
'Īlio Point			
2521B	MIP3a	0.386 ± 0.019	MIS 5e eolianite
2521A	MIP1a	0.552 ± 0.025	MIS 5e eolianite
Mo'omomi			
2522C	MMM2a	0.470 ± 0.002	MIS 5e eolianite
2522D	MMM1a (1)	0.470 ± 0.005	MIS 5e eolianite
2522E	MMM1a (2)	0.433 ± 0.008	MIS 5e eolianite
Kaua'i			
Makawehi			
2525B	KMW2a	0.441 ± 0.011	MIS 5e eolianite
2525C	KMW3a	0.478 ± 0.013	MIS 5e eolianite
Aweoweonui Beach			
2527	KAA1a	0.420 ± 0.002	MIS 5e eolianite
2706	KAA1a	0.444 ± 0.000	MIS 5e upper shore sands
Barking Sands			
2839	KBS1z	0.465 ± 0.010	Late Pleistocene sands
2838	KBS2a	0.528 ± 0.050	MIS 5e upper foreshore sands

[a] Analytical error for multiple analyses of same vial sample. A/I values for the Inter-Laboratory Comparison Standards ILC-A, ILC-B, and ILC-C measured at Northern Arizona University (1998–1999) were 0.148 ± 0.004, 0.498 ± 0.022, and 1.049 ± 0.025. These values are well within the range measured for the same samples by other laboratories (Wehmiller 1984).

[b] Holocene deposits composed largely of reworked Pleistocene sands.

[c] Dates from Fletcher et al. (1999).

[d] Higher ratio probably the result of shallow burial (<1 m).

o-phthalaldehyde (OPA) and fluorescence detection. Each sample solution was analyzed three to five times and the results averaged. The coefficient of similarity (σ/X) of average peak-height A/I ratios was typically <3%, which represents the internal reproducibility (analytical precision). The analytical precision accompanies all data presented in Table 2. Error resulting from analyses of several different samples from the same geological

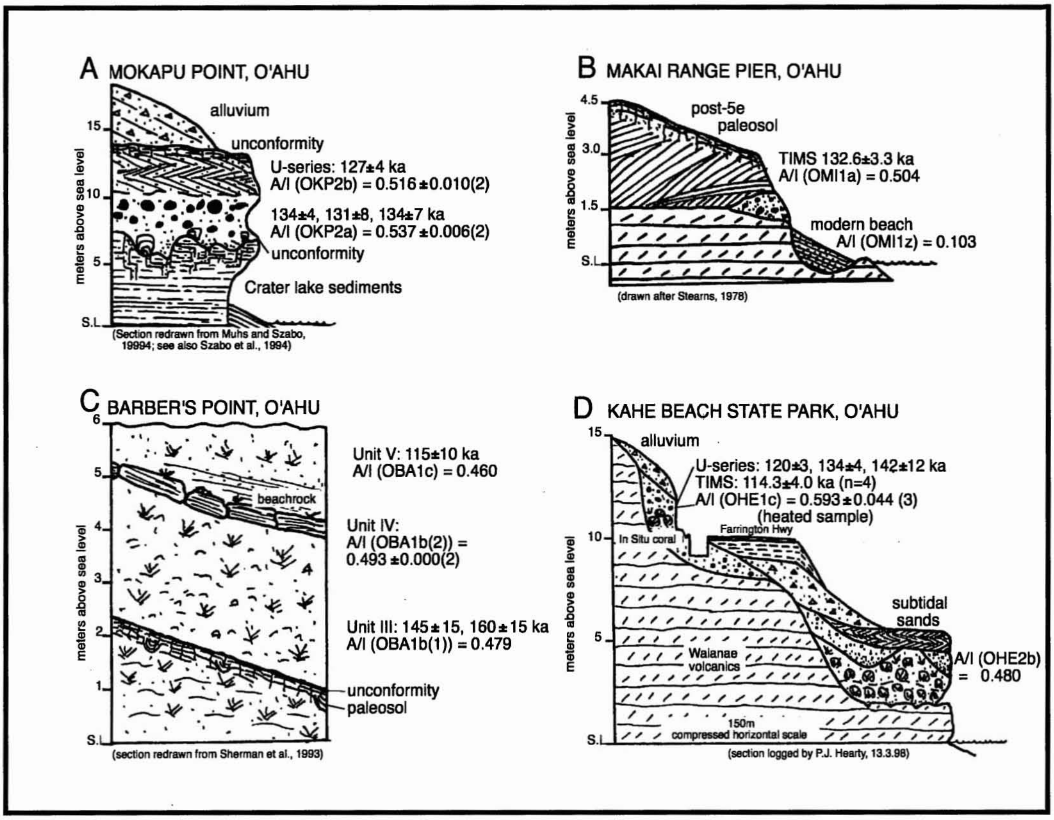

FIGURE 4. Stratigraphic sections of U-series calibration sites discussed in text. Mean U-series ages and whole rock A/I ratios are plotted in each section. *A*. Mōkapu Point, O'ahu (in situ reefs at +5.5 m and +9 m) from Muhs and Szabo (1994). *B*. Makai Range Pier, O'ahu. Shoreline deposits at +2 m dated at 134 ka (Szabo et al. 1994). *C*. Barbers Point, O'ahu. Section indicating two high stand events at +5.5 m and >+6 m asl (Sherman et al. 1993). *D*. Kahe Point Beach Park with +5 and +10 m paleoshoreline levels (Hearty section). U-series ages are from (1) Muhs and Szabo (1994), (2) Easton and Ku (1981), and (3) Szabo et al. (1994).

unit is reported in all other tables and figures in the format of the mean (X) $\pm$ 1 standard deviation (1σ), and the number of samples analyzed (in parentheses) (e.g., 0.464 $\pm$ 0.042 [$n = 20$]). To monitor analytical drift and to facilitate comparison with data from other laboratories, the NAU laboratory routinely calibrates with the Interlaboratory Comparative Standards of Wehmiller (1984) (see footnote in Table 2).

CALIBRATION SITES FOR THE LAST INTERGLACIAL (MIS 5e)

Independently dated Pleistocene sites in O'ahu were selected as the control group for calibration of the AAR method. At most of the undated sites, it was possible to determine on the basis of field criteria whether deposits were Holocene or late or middle Pleistocene. Stratigraphic sections are illustrated in Figures 4–6, which include previously published U-series dates and the A/I and radiometric data from Tables 1 and 2.

O'ahu

MŌKAPU POINT. The geology of Mōkapu Point and Ulupa'u Crater has been the subject of geological investigations for over a century (Dana 1890, Stearns and

Vaksvik 1935, Wentworth and Hoffmeister 1939, Winchell 1947, Gramlich et al. 1971). Although undated, the eruption of Ulupa'u Crater probably took place during the early to early-middle Pleistocene, probably among the older "rejuvenation stage" volcanics (Ko'olau) of O'ahu (Clague and Dalrymple 1989). Sometime after the construction of the crater, a lake formed within its walls. Through much of the middle Pleistocene, both lacustrine and colluvial sediments filled the crater to at least 20 m above current sea level. A considerable number of species of fossil birds have been found within the lake sediments (James 1987 and unpubl. data) and provide an important snapshot of avian evolution during the middle Pleistocene. Before the Waimānalo transgression (~125 ka), marine erosion removed the eastern half of the crater, and reef flats from that transgression directly abut the cliffs of crater fill. A composite stratigraphic section of the Waimānalo deposits at Mōkapu Point (after Muhs and Szabo 1994) is shown in Figure 4*A*.

Ku et al. (1974) determined alpha U-series ages of the Waimānalo deposits at Mōkapu to be 131 ± 8 ka at +7.8 m and 134 ± 7 ka at +11 m from coral cobbles in the upper conglomerate. Muhs and Szabo (1994) provided alpha U-series ages of 134 ± 4 ka and 127 ± 4 ka from coral heads in growth position at +8.5 m and marine conglomerate at +12.5 m. Fourteen TIMS ages from a study by Szabo et al. (1994) ranged from 123 to 141 ka, of which four samples from growth-position corals in the conglomerate at +7.3 m and +8.6 m yielded ages of 130 ± 2 ka and 124 ± 3 ka, respectively. For dating comparison by AAR analysis, samples were collected at Mōkapu Point from the reef matrix at +5 m and from shallow subtidal sands at +10 m.

The two samples from reef matrix sediments at +5 m (OKP2a) produced a mean A/I ratio of 0.537 ± 0.006 (volcanic grains excluded) (Table 2). Two similarly prepared samples from +10 m (OKP2b) generated a mean A/I ratio of 0.516 ± 0.010. Thus, A/I ratios from Mōkapu are in stratigraphic order and yield ratios reflecting a several-thousand-year interval, in agreement with previously published U-series ages.

MAKAI RANGE PIER. This simple outcrop exposes beach conglomerate at +2 m (Figure 4*B*). The deposit was attributed to the Lē'ahi shoreline of Stearns (1978), which he viewed as a regression phase from the Waimānalo high stand. At face value, a single TIMS U-series age of 132.6 ± 3.3 ka (Szabo et al. 1994) appears to contradict Stearns' late MIS 5e interpretation. Both the Pleistocene conglomerate and modern beach sands were sampled for AAR. A single A/I ratio of 0.504 suggests a correlation with Mōkapu and Barbers Points and agreed with the older MIS 5e TIMS age of Szabo et al. (1994).

BARBERS POINT. Evidence of two sea-level oscillations separated by a minor regression were interpreted from the sequence by Sherman et al. (1993) (Figure 4*C*). Alpha U-series dating provided three wide-ranging ages of 115 ± 10 ka, 145 ± 15 ka, and 160 ± 15 ka. It is clear from stratigraphic relations and the younger MIS 5e U-series age (115 ± 10 ka), however, that the deposits are last interglacial. Lower to upper units II (in situ bafflestone), IV (beachrock slabs of grainstone), and V (in situ bafflestone) were collected for AAR analysis from Sherman et al.'s (1993) (Figure 4*C*) section at Barbers Point. Resulting A/I ratios are, respectively, 0.479 ($n = 1$), 0.493 ± 0.000 ($n = 2$), and 0.460 ($n = 1$).

The lower two units II and IV were interpreted by Sherman et al. (1993) to belong to the older sea-level oscillation (128 ka?) and the upper unit V to the younger (120 ka?). Despite the variable composition of the limestone, A/I ratios confirm a similar older age of the lower two units, and the upper unit indicates a somewhat younger age. The mean A/I ratio of 0.481 ± 0.016 ($n = 4$) from the deposit closely corresponds to the Mōkapu section A/I ratio of 0.526 ± 0.014 ($n = 4$), suggesting a temporal correlation between the deposits on opposite sides of O'ahu. The range of A/I ratios suggests a depositional interval of several thousand years, rather than the wide range of U-series and electron spin resonance (ESR) ages (30 to 45 ka) reported in Sherman et al. (1993).

KAHE POINT BEACH PARK. Reef deposits form a broad terrace at around +5.5 m at

Kahe Point, and coral and volcanic boulder conglomerate rises to nearly +12 m eastward (east side of Farrington Highway) of the point (Figure 4*D*). Uranium dates have only been obtained for the +12 m upper conglomerate. The lower reef deposit has not been previously dated. Easton and Ku (1981) ascertained an age of 142 ± 12 ka for the upper conglomerate, Muhs and Szabo (1994) determined two ages at 120 ± 3 ka and 134 ± 4 ka, and Szabo et al. (1994) derived TIMS ages ranging from 110 ± 4 ka to 117 ± 2 ka. Considering the conglomeratic nature of the +12 m deposit, a range of ages is expected, and the youngest ages (120 to 115 ka?) likely approach the apparent age of the depositional event late in MIS 5e. However, coral ages between 110 and 115 ka are problematic because they center on the MIS 5d low stand. AAR samples from the previously undated +5.5 m terrace yielded a MIS 5e ratio of 0.480 (1), and the conglomerate at +12 m produced three ratios averaging 0.593 ± 0.044. In the +12 m deposit, it was necessary to collect the AAR sample from less than ideal conditions (<1 m shallow burial of sample); it is likely that the sample experienced some surface heating, resulting in a somewhat elevated A/I ratio.

AAR CORRELATION OF UNDATED PLEISTOCENE AND HOLOCENE SITES

O'ahu

KAHUKU POINT. Growth position corals, capped by a coarse conglomerate and eolianite, are exposed near sea level at Kahuku Point on the northeastern end of O'ahu. Ku et al. (1974) obtained an alpha U-series age of 137 ± 11 ka from the reef unit and 115 ± 6 ka from the conglomerate. Subsequently, Szabo et al. (1994) determined three TIMS ages averaging 121 ± 3 ka from the reef unit. Collections for AAR were only possible from the stratigraphically youngest Pleistocene eolianite unit in the section, which yielded A/I ratios of 0.397 ± 0.000 ($n = 2$). Constrained by stratigraphy and TIMS ages (<121 ka), these uppermost eolianites may record the final MIS 5e regression between 120 and 115 ka or perhaps a subsequent high stand later in MIS 5.

LANILOA PENINSULA. Stearns (1978) classified the eolian deposits at Laniloa Peninsula along the east coast of O'ahu with the middle Pleistocene Lā'ie high stand of sea level. Our field investigation revealed that the peninsula is actually composed of at least three eolian units, separated by soils. (These units are conspicuous on nearby Kukuiho'olua Island.) We concur with Stearns' middle Pleistocene interpretation of the landward part of the peninsula, but with the addition of a younger seaward eolianite of late Pleistocene age (MIS 5e or 5a?) forming the eastern part of the peninsula. Our collections from the most landward and the most seaward units indicated these eolianites to be middle Pleistocene (MIS 7–9) and late Pleistocene (late MIS 5e or 5a?), with A/I ratios of 0.640 (1) and 0.379 (1), respectively.

MĀKUA VALLEY. A road cut along Farrington Highway 0.5 km south of the mouth of Mākua Stream and 1 km north of 'Ōhikilolo exposes loose, carbonate-rich intertidal sediments and growth position *Porites* corals up to +9 m. Stearns (1974) described another exposure at lower elevation along the beach in the vicinity of our site. A whole-rock A/I ratio from the site yielded a ratio of 0.550. Although somewhat high, the A/I ratio and the similarity of the site to the stratigraphy of Kahe Point Beach Park point to a correlation with MIS 5e.

'ŌHIKILOLO. In situ Pleistocene reef forms the base of the section, which is succeeded by interbedded fluvial conglomerate and dense, brown organic (marsh?) peat and clays dated at 4990 ± 60 yr B.P. (Table 1). The fluvial conglomerate and peat are truncated by intertidal beachrock grainstone, which is, in turn, capped by a complex series of brown to reddish brown, silty to sandy colluvial deposits. Spherical borings 3–4 cm in diameter (*Echinometra*) up to +2 m high in the beachrock indicate that sea level rose to this level at some point during the Holocene. The bored beachrock deposits and marsh peat most likely correspond with a mid-Holocene

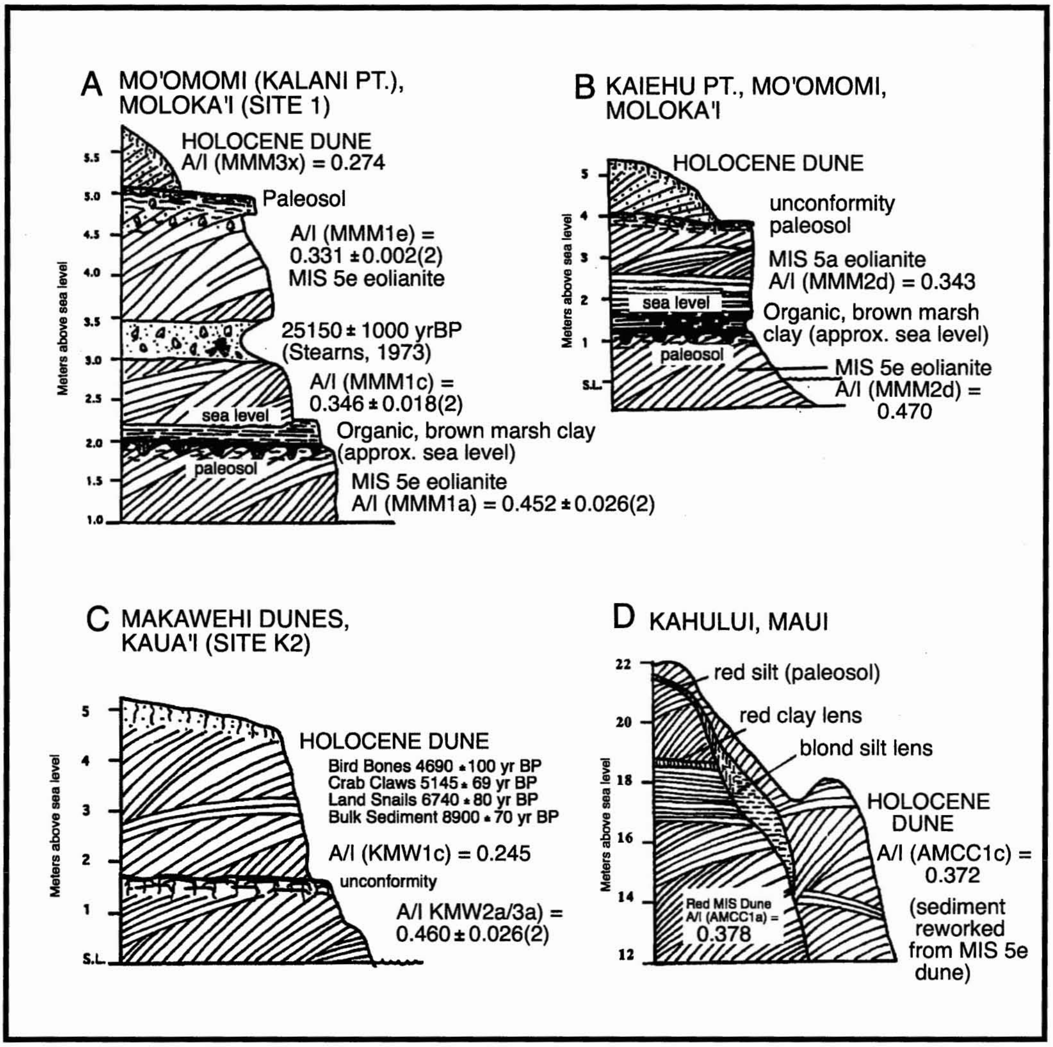

FIGURE 5. Stratigraphic sections of several "test sites" for the AAR method. Whole-rock A/I ratios (plotted in sections) are used for correlation of undated sites with calibration sites (Figure 4). *A*. Kalani Point, Mo'omomi dunes, Moloka'i: Late Pleistocene and Holocene dune sequence. *B*. Kaiehu Point, Moloka'i. *C*. Makawehi, Kaua'i: Pleistocene and Holocene sequence of eolianite. *D*. Community college site, Kahului, Maui. Whole-rock A/I ratios indicate that "Holocene" dunes were largely reworked from Pleistocene dunes.

high stand of sea level around +2 m, elsewhere dated at approximately 3500 yr B.P. (Jones 1992, Fletcher and Jones 1996, Grossman and Fletcher 1998). An A/I ratio of 0.215 (1) reflects a younger age than the underlying organic clays at 4990 yr B.P. and an older age than the 3500 yr B.P. high stand. It appears that around 5000 yr B.P., a beach barrier was established, impounding local island drainage and forming a slackwater marsh.

Moloka'i

Pleistocene eolianites capped by thick calcrete and orange-brown soils are exposed at the base of sections at Mo'omomi (Figure 5*A,B*) and 'Īlio Point on Moloka'i. AAR samples from these sites provided mean A/I ratios of 0.455 ± 0.020 ($n = 3$) and 0.469 ± 0.117 ($n = 2$), respectively, confirming a correlation with MIS 5e calibration sites.

Stearns (1973) described the dunes at Kalani Point (Figure 5*A*) where a fossil flightless anseriform was discovered (holotype of *Thambetochen chauliodous* Olson & Wetmore [1976], discovered by Joan Aidem of Moloka'i). Stearns (1973) interpreted the dunes as glacial age, partly on the basis of a $25{,}150 \pm 1000$ yr B.P. ^{14}C date on land snails taken from the intercalated soil. However, the geological setting of the units beneath a thick calcrete and pale brown (10YR 6/3) soil clearly places the dunes in the Pleistocene, most likely associated with high stands of sea level during the last interglaciation.

A/I ratios of 0.452 ± 0.026 from the base of the Kalani section are correlated with MIS 5e. This basal unit is capped by a red-orange soil and higher by a dense, clayey brown peat. A/I ratios from middle eolianite units above the brown peat and bracketing Aidem's fossil level yield a solid mean of 0.339 ± 0.006 ($n = 6$). Obtained from several sites along the coastline, these ratios are too low for MIS 5e. We interpret these ratios to represent a high stand of sea level late in the last interglaciation (sensu lato) at MIS 5a around 80 ka, which has been observed elsewhere along relatively stable coastlines (Vacher and Hearty 1989, Ludwig et al. 1996, Hearty and Kaufman 2000). The level of the brown peat approximates relative paleosea level of circa +2.0 m during the late interglacial high stand.

A younger generation of Holocene dunes between Mo'omomi Beach and Kapālauo'a Point were described in detail by Wentworth (1925) and Stearns (1973) (Figure 5*A,B*). These dunes have been an important source of fossil bird bones (Olson and Wetmore 1976, Olson and James 1982*a,b*). The location of these fossils near and parallel to the coast, as well as the presence of well-developed soils in isolated remnant patches in the same zone indicate that the original dunes may have formed as a coastal dune cordon. We suggest that dune migration 8 km inland occurred recently as blowouts, initiated by environmental degradation from deforestation, trampling, and overgrazing by ruminants and excessive agricultural use since the arrival of humans in Hawai'i around 1500 yr ago (Athens 1997). A/I ratios from two sites (MMM3x/4x) were 0.274 and 0.246, respectively. The MMM4x ratio of 0.246 ± 0.016 was determined from two bulk sediment samples from the same collection that produced a ^{14}C age of 8360 ± 60 yr B.P. (Table 1). A modern beach sample from Mo'omomi returned an A/I ratio of 0.126, indicating that reworking of Pleistocene sediments along that shoreline is not significant. A whole-rock sample from a fossil beach ridge along the southern coast west of Kaunakakai yielded a mid-Holocene ratio of 0.270. This ratio is directly associated with two whole-rock ^{14}C ages of 4750 ± 70 and 5730 ± 60 yr B.P. (Fletcher et al. 1999).

Extensive Holocene dune deposits also cover most of 'Īlio Point. Land snail shells associated with the bird fossils have yielded ^{14}C ages of 5245 ± 60 and 5510 ± 65 yr B.P. (Olson and James 1982*a*) (Table 1) for these dunes. Like Mo'omomi, destruction of the vegetative cover probably initiated reactivation of the dunes in more recent times. A/I ratios from the 'Īlio Point dunes (MIP6x = 0.277; MIP4x = 0.308; MIP2x = 0.262) were concordant with those from Mo'omomi. Two "Holocene" sediment samples from 'Īlio Point, however, yielded older ^{14}C ages of $12{,}740 \pm 90$ and $12{,}710 \pm 90$ yr B.P. These older ages may be attributed to incorporation of a substantial percentage of Pleistocene grains into the Holocene samples. Furthermore, although providing a maximum (Holocene) age of dune sand formation, we cannot consider these dates to be accurate, because at that time sea level was positioned over 80 m lower than present (Fairbanks 1989). Because the −80 m contour lies several kilometers offshore of 'Īlio Point, it is improbable that substantial marine sedimentation could have occurred at that time on the current shoreline.

Kaua'i

Both Pleistocene and Holocene eolianites are present on the southeastern Makawehi–Māhā'ulepū coast of Kaua'i. Figure 5*C* shows a composite section (KMW1/3) near the fossil bird site "K2" of Olson and James (1982*a*). Farther north, an upper backshore Pleistocene deposit outcrops along the south end of a small pocket beach in Hā'ula Bay. Much older limestone (early Pleistocene?) is exposed on the north margin of the same bay. Samples from the Pleistocene eolianite returned A/I ratios of 0.460 ± 0.026 ($n = 2$) at Makawehi, 0.432 ± 0.017 ($n = 2$) at Hā'ula Beach, and 0.497 ± 0.045 ($n = 2$) at Barking Sands along the Mānā Plain. On the basis of these A/I ratios, these sites are correlated with the O'ahu control localities of MIS 5e age.

The Holocene dunes along the Makawehi and Hā'ula Bay coastline are notable for important bird fossil discoveries from 1976 to the present (Olson and James 1982*a,b*). A bulk sediment sample from the Makawehi dunes yielded an A/I ratio of 0.245 (1) and a ^{14}C age of 8900 ± 70 yr B.P. These data reflect the *maximum* age of the deposit, identifying the interval when sediments were formed offshore. Land snail, crab claw, and bird bone samples found within the dunes yielded ^{14}C ages of 6740 ± 80, 5145 ± 60, and 4690 ± 100 yr B.P. (Table 1), respectively. These ages reflect the *minimum,* or "occupation age" of the dune environment. Together they document a 2000- to 3000-yr interval between time of formation of the sediments offshore (ca. 8900 yr B.P.), emplacement of the dunes, stabilization by vegetation, and occupation of the dunes by organisms (5500 yr B.P.). The Polihale dunes of western Kaua'i have produced no fossils and are considerably younger than Makawehi, reflected by a submodern A/I ratio of 0.153 (1).

Maui

Extensive eolianite deposits in the vicinity of Kahului, Maui (Figure 5*D*), were examined and collected for AAR analysis. A/I ratios from two exposures of red-stained (2.5YR 3/6) eolianite near the community college (AMCC) and zoological gardens (AMZB) yielded concordant ratios of 0.378 (1) and 0.380 (1), equivalent to late MIS 5e. It is interesting that the stratigraphically younger eolianite, determined to be "Holocene" on the basis of field criteria (loose to weakly cemented light brown sand without capping calcrete and red soil), superimposed on the Pleistocene unit at AMCC (Figure 5*D*) and Nehe Point, returned A/I ratios of 0.372 (1) and 0.349 (1). With A/I ratios nearly identical to those from Pleistocene deposits, the most acceptable interpretation is that the bulk of "Holocene" eolianite along the north isthmus of Maui consists largely of reworked sediments of last interglacial age. Because the Pleistocene dunes are not firmly cemented, they are subject to reactivation through a number of human or natural processes including fire, deforestation by fire or overgrazing, prolonged aridity, or washover by tsunamis. Because of the absence of datable material, it is uncertain whether reactivation of the Kahului dunes took place previous to or since human arrival on the island. Unlike the mid-Holocene dunes of Moloka'i and Kaua'i, the Maui dunes have yielded no bird fossils, which possibly may be linked to diagenesis and/or the reworking of Pleistocene sands.

SUMMARY OF AMINOSTRATIGRAPHIC RESULTS

The Last Interglaciation, MIS 5e and 5a, Aminozones E and C

Four TIMS and alpha U-series dated sites in O'ahu provided age calibration for Aminozone E, the last interglaciation. The mean of A/I ratios from the calibration sites was 0.505 ± 0.027 ($n = 11$). Twelve "test sites" on Maui, O'ahu, Moloka'i, and Kaua'i, of previously uncertain geochronological age, produced a grand mean of 0.445 ± 0.058 ($n = 17$). Although the variance of the test sites (0.387–0.503) is statistically equivalent to that of the calibration sites (0.478–0.532), the somewhat lower mean of the test sites may be explained by one or more of the following: (1) Most test site collections were from late MIS 5e eolianite. This eolianite marks the regression from the high stand (115–120 ka?) and thus marginally postdates the emergent marine deposits of the calibration sites (135–120 ka). We interpret the

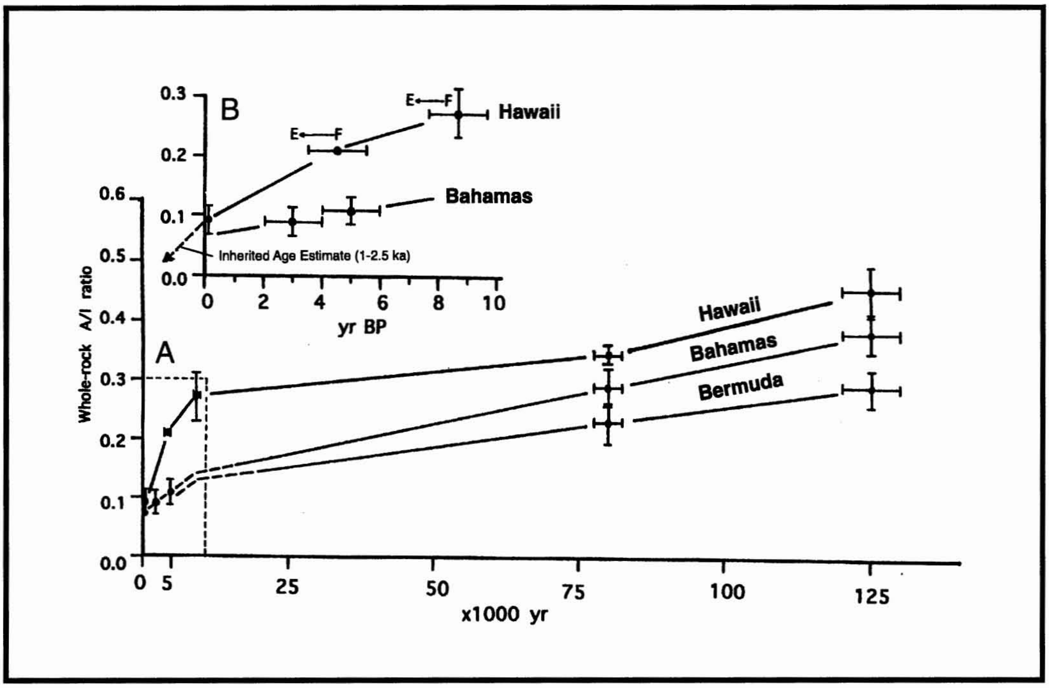

FIGURE 6. Comparison of U-series and ^{14}C calibrated whole-rock epimerization data from Bermuda, the Bahamas, and the Hawaiian Islands for the past 125 ka (*A*) and for the Holocene (*B*). Kinetic pathways show similar trends over the sample interval, with higher rates of epimerization occurring in the Hawaiian Islands as a result of assumed warmer thermal histories among the islands. Significantly higher rates during the Holocene of Hawai'i (upper curve in *B*) may be due to local effects, warmer temperature history, or a degree of mixing with older deposits. Whatever these effects, they are negligible in Pleistocene deposits. E ← F represents age of formation ("F") versus age of emplacement ("E") in *B*. Dashed line with arrow along the vertical axis in *B* is an extrapolation of the curve and an approximation of "inherited age" of modern beach deposits.

entire range of values encompassed in the means of 0.505 ± 0.027 and 0.445 ± 0.058 as equivalent to the duration of MIS 5e, documented by uranium ages between 135 and 115 ka; (2) A significantly lower A/I ratio of 0.339 ± 0.006 ($n = 6$) from the "middle eolianite" unit Mo'omomi, Moloka'i, situated above MIS 5e marine deposits and capping soil probably represents a near-present high stand late in the interglacial (sensu lato) or MIS 5a. The possibility remains that eolianite units at Kahuku and Laniloa, O'ahu, could also correspond with MIS 5a. Additional tests are warranted on these sites; (3) The possibility of local and regional temperature varibility of the test sites (e.g., windward versus leeward); and (4) Some sites may be more susceptible to reworking (receiving old sediment) than others and may account for some of the variability in A/I ratios.

The Holocene, MIS 1, and Aminozone A

Three subgroups of A/I ratios are recognized among Holocene deposits of the islands. Samples from modern beach and recent dune deposits from several islands return A/I ratios averaging 0.112 ± 0.025 ($n = 7$) (Table 2). Extrapolation of the A/I versus ^{14}C age (Figure 6*B*, dashed line) estimates an "inherited age" of 1000 to 2500 yr for the modern beach and dunes. A second unit is represented by +2 m beachrock at 'Ōhikilolo in O'ahu, which yielded a ratio of 0.215. Independent studies (Jones 1992, Fletcher and Jones 1996, Grossman and Fletcher 1998) suggest a correlation of the beachrock with a mid-Holocene high stand. Because of the apparent "inherited age" of the beachrock sand, the A/I ratio indicates a time of formation of the sand some 1000–2500 yr earlier. The oldest Holocene subgroup from dune sites on Moloka'i and Kaua'i yielded consistent ratios averaging 0.266 ± 0.022 ($n = 8$), which equate with bulk sediment ages of 8600 ± 70 yr B.P. ^{14}C ages on organisms inhabiting the dunes center on 5500 yr B.P., bracketing the time of emplacement of the dunes within this interval.

Comparison of Whole-Rock Ratios with Those of Bermuda and the Bahamas

As predicted by epimerization kinetic models (Miller and Brigham-Grette 1989), the increasing temperature histories (MAT by proxy) from Bermuda, Bahamas, and Hawai'i yield incrementally higher overall mean ratios of 0.29 ± 0.03, 0.38 ± 0.02, and 0.47 ± 0.05, respectively, for MIS 5e (Figure 6 and Table 3). In finer detail, MIS 5e sites from similar latitudes (~21° N) in the Bahamas and Hawai'i produce similar ratios. For example, mean island A/I ratios from Inagua (0.477 ± 0.014 [$n = 3$]) in the Bahamas (Hearty and Kaufman 2000) and those from Kaua'i (0.450 ± 0.022 [$n = 5$]), O'ahu (0.485 ± 0.055 [$n = 15$]), and Moloka'i (0.462 ± 0.061 [$n = 5$]) show close correspondence (Figure 3). Because of the substantially higher epimerization rate during the Holocene (Hearty and Aharon 1988, Hearty and Dai Pra 1992, Miller et al. 1999), the separation of A/I ratios between the Bahamas and Hawai'i are greater; the whole-rock ratio at 5000 yr B.P. from the Bahamas is 0.11 ± 0.03, whereas bulk sediment ages of 8600 yr B.P. from Hawai'i average 0.27 ± 0.02. This large degree of separation of ratios appears to be primarily the result of the warmer temperature history of Hawai'i during the Holocene, but may also be affected by "fast" epimerization grain constituents and some degree of mixing with older sediments.

Overall, whole-rock A/I ratios mirror morphostratigraphic relations, increase appropriately with greater stratigraphic age, and produce concordant numbers from both independently dated and stratigraphically equivalent age deposits from widespread localities.

IMPLICATIONS OF A HAWAIIAN AMINOSTRATIGRAPHY

Sea Level History and Lithospheric Flexure

The AAR results correlate 16 last interglacial sites on four Hawaiian islands. Calibration is provided from four O'ahu sites for the remaining 12 sites of previously uncertain geochronological age. At each of the calibration sites, sedimentary structures and in situ coral growth indicated higher than current sea levels ranging from +5.5 to +9 m above sea level, supporting the sustained uplift of O'ahu. In comparison with Bermuda and Bahamas MIS 5e sites, the difference between both early and late high stand levels of 3 m would yield an O'ahu uplift rate of 0.024 m/ka. If this rate were applied to the interpreted MIS 5a site at Kalani Point, Moloka'i, it would predict an 80 ka sea level 1.9 m above present, given previous documentation of a near-present MIS 5a sea level on stable coastlines (Vacher and Hearty 1989, Hearty 1998). The presence of a marsh peat at +2 m associated with MIS 5a eolian deposits at Kaiehu and Kalani supports a similar rate of uplift between O'ahu and Moloka'i. Older emergent carbonate deposits have been described on Moloka'i (Grigg and Jones 1997), but their possible origin by tsunamis (Moore et al. 1994) as well as their ages remain equivocal. On Hawai'i, Maui, and Kaua'i, only eolian and uppermost backshore deposits have been observed above sea level, suggesting subsidence at rates of greater than 0.048 m/ka (6 m/125 ka) of these islands. In general, these findings lend support to the Grigg and Jones (1997) lithospheric flexure model.

The ^{14}C and AAR data from Holocene deposits indicate that a major depositional event occurred between 8600 and about 5500 yr B.P. Extensive dunes were emplaced along windward coastlines as postglacial sea level

TABLE 3

CORRELATION OF HAWAIIAN AAR AMINOZONES (A ZONE), MARINE ISOTOPE STAGES (MIS) WITH BERMUDA AND THE BAHAMAS

MIS CORRELATION	A ZONE	BERMUDA SITE/FM (Hearty et al. 1992)	MEAN W-R A/I RATIO	ELEUTHERA SITE/FM (Hearty 1998)	MEAN W-R A/I RATIO	HAWAI'I SITE/FM (this study)[a]	MEAN W-R A/I RATIO
Modern Recent	A3	Modern beach	0.12 ± 0.01 (2)	Modern beach	0.05[b] ± 0.02 (3)	Modern beaches and dunes	0.11 ± 0.03 (6)
Late 1	A2			Singing Sands	**0.09 (1)**	ʻŌhikilolo, OA	**0.22 (1)**
Mid 1	A1			Windermeer Island	**0.10 (1)**	Makawehi, KA; Moʻomomi, MO	**0.27 ± 0.02 (8)**
5a	C	Southampton Fm	**0.23 ± 0.03 (3)**	Whale Point	0.29 ± 0.03 (5)	Kalani Pt., MO	0.34 ± 0.01 (6)
Late 5e	E2	Rocky Bay Fm	**0.29 ± 0.03 (12)**	Boiling Hole; Savannah Sound	**0.38 ± 0.02 (12)**	MA, MO, OA, KA	**0.45 ± 0.06 (17)**
Mid–Early 5e	E1					Mōkapu; Barbers Pt., OA	**0.51 ± 0.03 (11)**
7	F	Belmont Fm	**0.49 ± 0.04 (11)**	Goulding Cay, The Cliffs	0.58 ± 0.01 (3)	Laniloa, OA	0.64 (1)
9	G	Upper Town, Hill Fm	0.56 ± 0.02 (11)	Goulding Cay	**0.67 ± 0.05 (16)**		
11	H	Lower Town, Hill Fm	**0.67 ± 0.03 (6)**			Kaʻena, Waiʻanae H.C., OA	**0.81 ± 0.08 (4)**

Note: U-series or ^{14}C calibrated or constrained A/I ratios are in bold type. Data presented in the format 0.43 ± 0.05 (15) (mean ± 1 sigma [number of samples analyzed per stratigraphic unit]).

[a] HI, Hawaiʻi; MA, Maui; OA, Oʻahu; MO, Molokaʻi; KA, Kauaʻi.

[b] Modern ooid shoal samples from Exuma Cays.

approached the current datum, rising from −15 m to near present during this 3000-yr interval of the Holocene (Grossman and Fletcher 1998). Evidence of a higher than present sea level around 5000 yr B.P. is inferred from beachrock with *Echinometra* borings and marsh peat above +2 m at ʻŌhikilolo, Oʻahu.

The sediments composing the modern beaches and recent dunes of the Hawaiian Islands are marked by A/I ratios averaging 0.112 ± 0.025, which reflects the interval of formation and aggregation or "inherited age" of modern coastal sediments.

Dune Bird Fossils

Previous ^{14}C dates obtained from land snails and crab claws associated with bird fossils at ʻĪlio Point, Molokaʻi, and Makawehi, Kauaʻi, as well as from bird bones themselves (Olson and James 1982*a*), although once considered equivocal, now appear perfectly in line with the maximal ^{14}C ages for the dune sand itself (Table 1), supported by concordant AAR ratios (Table 2). A Holocene age is inferred from the loosely consolidated to unconsolidated carbonate sands composing the dunes, with hollow root casts typical of very young deposits in other locations (White and Curran 1988), their youngest stratigraphic position, and the weak development of soils.

The ʻĪlio Point and Makawehi sites are of further interest because the sands here are perched above erosional cliffs of basalt that would have severed the supply of sand. Well before 5500 yr B.P., organisms inhabited the dunes, which were presumably stabilized by vegetation. The fossils from which the ^{14}C dates were obtained are unlikely to have been buried after the sand source was cut off, suggesting in turn that the erosional features along these coasts are younger than indicated by the ^{14}C dates.

Radiocarbon dates from dune sites and other fossil localities have shown that most (maybe all) of Hawaiʻi's extinct fossil birds were still alive in the mid- to late Holocene, well after any climatic changes of the Pleistocene that might be invoked as possible causes of extinction (Olson and James 1982*a*, 1991, James et al. 1987, Paxinos 1998, Burney et al. 1999). Indeed, it may be that human activity had a profound impact on the landscape itself, where dunes that were perhaps stable and vegetated for several thousand years were defoliated and deflated. At Moʻomomi, parabolic and "blowout" dunes migrated in some cases several kilometers inland, perhaps facilitated by sustained trampling and grazing by ruminants. It was this renewed activity and transport of the dunes that exposed the avian fossils that once lay buried within the dunes.

At Makawehi, Kauaʻi, hawk bones reported by Olson and James (1997) came from deposits that, on the basis of field relationships, are also interpreted to be Pleistocene. Whole-rock A/I ratios from this deposit, situated beneath a thick calcrete and paleosol, yield ratios that correlate directly with sites on Oʻahu. Mean A/I ratios are 0.460 ± 0.026 ($n = 2$), equivalent to MIS 5e.

Exposure of previously buried fossils in the dunes appears to be slow, especially on Kauaʻi. All of the major outcrops of bird fossils in the Makawehi dunes were found when these dunes were first explored paleontologically in 1976. Since then, little else of significance has been found eroding naturally in the dunes despite two powerful hurricanes that passed over this area in 1982 (ʻIwa) and 1992 (ʻIniki). The process is being slowed further by spread of vegetation, especially introduced plants such as *Casuarina* and *Prosopis*.

Two dune sites that have produced fossil birds are Pleistocene rather than Holocene in age. At Site 1 (Figure 5*A*), at Moʻomomi, Molokaʻi, the complete articulated skeleton of an extinct flightless waterfowl (holotype of *Thambetochen chauliodous* Olson & Wetmore, 1976) was recovered by Joan Aidem from a weak soil interbedded with eolianite (Stearns 1973). Whole-rock samples from Kalani Point yielded MIS 5e (125 ka) A/I ratios from the base of the section, probable MIS 5a (80 ka) ratios from the middle units containing the fossils, and Holocene (8–5 ka) ratios from the upper part (Figure 5*B*, Table 2).

CONCLUSIONS

U-series and ^{14}C calibration of whole-rock A/I ratios has enabled the correlation and dating of numerous sites of previously unknown or uncertain geochronological age. Three aminozones are recognized: (1) Aminozone A, represented by three subgroups of the Holocene with correlated ages of 8500–5500 yr B.P., 5000 to 3000 yr B.P., and modern beaches and dunes. The "inherited" ages of whole-rock samples from these subgroups average about 1000–2500 yr; (2) Aminozone C (MIS 5a, 80 ka), tied to eolianite deposits on the north shore of Moloka'i associated with *Thambetochen chauliodous,* a flightless anseriform that was once abundant in the Hawaiian Islands; and (3) Aminozone E (MIS 5e, 125 ka), composed of numerous independently dated last interglacial sites from O'ahu, from which it is possible to make correlations with noncoraliferous deposits on several islands. Older deposits and aminozones have also been defined and will be presented in forthcoming papers.

On the basis of the height of emergent shoreline deposits, these data confirm uplift rates on the order of 0.020 ± 0.005 m/ka on O'ahu and Moloka'i. Because emergent MIS 5e subtidal deposits are not observed above sea level on Hawai'i, Maui, and Kaua'i, these data also suggest subsidence rates in excess of 0.048 m/ka for those islands. These findings generally support the lithospheric flexure model of Grigg and Jones (1997).

Finally, our findings place time constraints on the extinction of a variety of avian forms that occupied the Hawaiian Islands through the late Quaternary up to historical times.

ACKNOWLEDGMENTS

We are indebted to A. Zeigler (Bishop Museum), D. Burney (Fordham University), and J. Aidem (Moloka'i) for sharing their knowledge of the natural history of the Hawaiian Islands. S. Anthony assiduously edited the manuscript. Work on Kaua'i and several ^{14}C dates were determined under NSF grant DEB-9707260 to D. Burney. Whole-rock AAR samples were analyzed under a collaborative agreement with the Amino Acid Laboratory of Northern Arizona University (D. Kaufman, director).

LITERATURE CITED

ATHENS, J. S. 1997. Hawaiian native lowland vegetation in prehistory. Pages 248–270 *in* P. V. Kirch and T. L. Hunt, eds. Historical ecology in the Pacific Islands. Yale University Press, New Haven, Connecticut.

BRETZ, J. H. 1960. Bermuda: A partially drowned late mature Pleistocene karst. Geol. Soc. Am. Bull. 71:1729–1754.

BURNEY, D. A., L. P. BURNEY, M. BURNEY, D. MCCLOSKEY, S. L. OLSON, H. F. JAMES, F. V. GRADY, W. L. WAGNER, W. KIKUCHI, D. KIKUCHI, R. GAGE II, and R. NISHEK. 2000. Holocene lake sediments in the Maha'ulepu Caves of Kaua'i: Evidence for a diverse biotic assemblage from the Hawaiian lowlands and its transformation since human arrival. Ecol. Monogr. (in press).

CLAGUE, D. A., and G. B. DALRYMPLE. 1989. Tectonics, geochronology and origin of the Hawaiian-Emperor Chain. Pages 188–217 *in* E. L. Winterer, D. M. Hussong, and R. W. Decker, eds. Geology of North America: The eastern Pacific Ocean and Hawaii. The Geological Society of America, Boulder, Colorado.

DANA, J. D. 1890. Characteristics of volcanoes, with contributions of facts and principles from the Hawaiian Islands. Dodd, Mead, and Company, New York.

DARWIN, C. 1839. On the structure and distribution of coral reefs. Reprint. Ward, Lock, Bowden and Company, London.

EASTON, W. H., and T. L. KU. 1981. $230^{Th}/234^{U}$ dates of Pleistocene deposits on Oahu. Bull. Mar. Sci. 31:552–557.

FAIRBANKS, R. G. 1989. A 17,000-year glacio-eustatic sea-level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature (Lond.) 342:637–642.

FLETCHER, C. H., III, and A. T. JONES. 1996. Sea-level highstand recorded in Holocene shoreline deposits on Oahu, Hawaii. J. Sediment. Res. 66:632–641.

FLETCHER, C. H., III (ED.), P. J. HEARTY, C. MURRAY-WALLACE, C. R. GLENN, C. E. SHERMAN, and B. POPP. 1999. Molokai field trip guidebook for participants. The non-steady state of the inner shelf and shoreline: Coastal change on the time scale of decades to millenia. University of Hawai'i, Honolulu.

GRAMLICH, J. W., V. A. LEWIS, and J. J. NAUGHTON. 1971. Potassium-argon dating of Holocene basalts of the Honolulu Volcanic Series. Geol. Soc. Am. Bull. 82:1399–1404.

GRIGG, R. W., and A. T. JONES. 1997. Uplift caused by lithospheric flexure in the Hawaiian Archipelago as revealed by elevated coral deposits. Mar. Geol. 141:11–25.

GROSSMAN, E. E., and C. H. FLETCHER. 1998. Sea level higher than present 3500 years ago on the northern main Hawaiian Islands. Geology 26:363–366.

HARE, P. E., and R. M. MITTERER. 1967. Non-protein amino acids in fossil shells. Carnegie Inst. Washington Year Book 65:236–364.

HEARTY, P. J. 1998. The geology of Eleuthera Island, Bahamas: A Rosetta Stone of Quaternary stratigraphy and sea-level history. Quat. Sci. Rev.17:333–355.

HEARTY, P. J., and P. AHARON. 1988. Amino acid chronostratigraphy of late Pleistocene coral reef sites: Huon Peninsula, New Guinea and the Great Barrier Reef, Australia. Geology 16:579–583.

HEARTY, P. J., and G. DAI PRA. 1992. The age and stratigraphy of Quaternary coastal deposits along the Gulf of Taranto (south Italy). J. Coastal Res. 8:882–905.

HEARTY, P. J., and D. S. KAUFMAN. 2000. Whole-rock amino stratigraphy and Quaternary sea-level history of the Bahamas. Quat. Res. 54. In press.

HEARTY, P. J., G. H. MILLER, C. E. STEARNS, and B. J. SZABO. 1986. Aminostratigraphy of Quaternary shorelines around the Mediterranean basin. Geol. Soc. Am. Bull. 97:850–858.

HEARTY, P. J., H. L. VACHER, and R. M. MITTERER. 1992. Aminostratigraphy and ages of Pleistocene limestones of Bermuda. Geol. Soc. Am. Bull. 104:471–480.

JACKSON, E., I. KOISUMI, G. DALRYMPLE, D. CLAGUE, R. KIRKPATRICK, and H. GREENE. 1980. Introduction and summary of results from DSDP leg 55, the Hawaiian-Emperor hot-spot experiment. Pages 5–41 *in* E. Jackson and I. Koisumi, eds. Initial reports of the deep sea drilling project. U.S. Government Printing Office, Washington, D.C.

JAMES, H. F. 1987. A late Pleistocene avifauna from the island of Oahu, Hawaiian Islands. Doc. Lab. Geol. Fac. Sci. Lyon 99:221–230.

JAMES, H. F., and S. L. OLSON. 1991. Descriptions of thirty-two new species of birds from the Hawaiian Islands: Passeriformes. Ornithol. Monogr. 46:1–88.

JAMES, H. F., T. W. STAFFORD JR., S. L. OLSON, D. W. STEADMAN, P. S. MARTIN, and P. MCCOY. 1987. Radiocarbon dates on bones of extinct birds from Hawaii. Proc. Natl. Acad. Sci. U.S.A. 84:2350–2354.

JONES, A. T. 1992. Holocene coral reef on Kauai, Hawaii. Evidence for a sea-level highstand in the central Pacific. Pages 267–271 *in* C. H. Fletcher and J. F. Wehmiller, eds. Quaternary coasts of the United States: Marine and lacustrine systems. SEPM Spec. Publ. 48:267–271.

KU, T. L., M. A. KIMMEL, W. H. EASTON, and T. J. O'NEILL. 1974. Eustatic sea level 120,000 years ago on Oahu, Hawaii. Science (Washington, D.C.) 183:959–962.

LUDWIG, K. R., D. R. MUHS, K. R. SIMMONS, R. B. HALLEY, and E. A. SHINN. 1996. Sea-level records at ~80 kyr from tectonically stable platforms: Florida and Bermuda. Geology 24:211–214.

MILLER, G. H., and J. BRIGHAM-GRETTE. 1989. Amino acid geochronology: Resolution and precision in carbonate fossils. Quat. Int. 1:111–128.

MILLER, G. H., J. W. MAGEE, B. J. JOHNSON, M. L. FOGEL, N. A. SPOONER, M. T. MCCULLOCH, and L. K. AYLIFFE. 1999. Pleistocene extinction of *Genyornis new-*

toni: Human impact on Australian megafauna. Science (Washington, D.C.) 283: 205–208.

MOORE, J. G., W. B. BRYAN, and K. R. LUDWIG. 1994. Chaotic deposition by a giant wave, Molokai, Hawaii. Geol. Soc. Am. Bull. 106:962–967.

MUHS, D. R., and B. J. SZABO. 1994. New uranium-series ages of the Waimanalo Limestone, Oahu, Hawaii: Implications for sea level during the last interglacial period. Mar. Geol. 118:315–326.

OLSON, S. L., and H. F. JAMES. 1982*a*. Fossil birds from the Hawaiian Islands: Evidence for wholesale extinction by man before Western contact. Science (Washington, D.C.) 217:633–635.

———. 1982*b*. Prodromus of the fossil avifauna of the Hawaiian Islands. Smithson. Contrib. Zool. 365:1–59.

———. 1991. Descriptions of thirty-two new species of birds from the Hawaiian Islands: Non-passeriformes. Ornithol. Monogr. 45:1–88.

———. 1997. Prehistoric status and distribution of the Hawaiian Hawk (*Buteo solitarius*), with the first fossil record from Kaua'i. Bishop Mus. Occas. Pap. 49:65–69.

OLSON, S. L., and A. WETMORE. 1976. Preliminary diagnoses of two extraordinary new genera of birds from Pleistocene deposits in the Hawaiian Islands. Proc. Biol. Soc. Wash. 89:247–258.

PAXINOS, E. E. 1998. Prehistoric anseriform diversity in the Hawaiian Islands: A molecular perspective from the analysis of subfossil DNA. Ph.D diss., Brown University, Providence, Rhode Island.

RUTTER, N. W., and B. BLACKWELL. 1995. Amino acid racemization dating. Pages 125–167 *in* N. W. Rutter and N. R. Catto, eds. Dating methods for Quaternary deposits: Newfoundland. Geological Association of Canada.

SHERMAN, C. E., C. R. GLENN, A. T. JONES, W. C. BURNETT, and H. P. SCHWARCZ. 1993. New evidence for two highstands of the sea during the last interglacial, oxygen isotope substage 5e. Geology 21:1079–1082.

STEARNS, H. T. 1973. Geologic setting of the fossil goose bones found on Molokai Island, Hawaii. Occas. Pap. Bernice Pauahi Bishop Mus. 24:156–163.

———. 1974. Submerged shorelines and shelves in the Hawaiian Islands and a revision of some of the eustatic emerged shorelines. Geol. Soc. Am. Bull. 85:795–804.

———. 1978. Quaternary shorelines in the Hawaiian Islands. Bernice P. Bishop Mus. Bull. 237:1–57.

STEARNS, H. T., and K. N. VAKSVIK. 1935. Geology and ground-water resources of the island of Oahu, Hawaii. O'ahu Division of Hydrography, Honolulu.

SZABO, B. J., K. R. LUDWIG, D. R. MUHS, and K. R. SIMMONS. 1994. Thorium-230 ages of corals and duration of the last interglacial sea-level high stand on Oahu, Hawaii. Science (Washington, D.C.) 266:93–96.

VACHER, H. L., and P. J. HEARTY. 1989. History of stage-5 sea level in Bermuda: With new evidence of a rise to present sea level during substage 5a. Quat. Sci. Rev. 8:159–168.

WATTS, A. B., and U. S. TEN BRINK. 1989. Crustal structure, flexure, and subsidence history of the Hawaiian Islands. J. Geophys. Res. 94:10,473–10,500.

WEHMILLER, J. F. 1984. Interlaboratory comparison of amino acid enantiomeric ratios in fossil Pleistocene mollusks. Quat. Res. 22:109–120.

WENTWORTH, C. K. 1925. The desert strip of West Molokai. Univ. Iowa Stud. Nat. Hist. 11:41–56.

WENTWORTH, C. K., and J. E. HOFFMEISTER. 1939. Geology of Ulupau Head, Oahu. Geol. Soc. Am. Bull. 50:1553–1572.

WHITE, B., and H. A. CURRAN. 1988. Mesoscale physical and sedimentary structures and trace fossils in Holocene carbonate eolianites from San Salvador, Bahamas. Sediment. Geol. 55:163–184.

WINCHELL, H. 1947. Honolulu Series, Oahu, Hawaii. Geol. Soc. Am. Bull. 58:1–48.